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WIND ESTIMATION FROM GEOSTATIONARY-SATELLITE PICTURES

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ABSTRACT

The motion of properly selected clouds derived from photographs taken by the geostationary Advanced Technology Satellites provides estimates of the wind at cloud level. A large number of low- and high-cloud motions near rawin stations are compared to the balloon-derived winds to determine the levels at which these wind estimates might be used for map analyses and to assess their accuracy at those levels.

For this sample, velocities of lower clouds correspond best to winds at 3,000 ft, while upper cloud velocities correspond best to winds at 30,000 ft. The median vector deviation of the cloud velocities from observed winds is 9 and 17 kt at 3,000 and 30,000 ft, respectively. Direction deviations are modest; therefore, these wind estimates are representative of the actual flow patterns in the lower and in the upper troposphere.

Causes contributing to deviations are (1) uncertainty of cloud height, (2) nonadvective cloud motion, (3) photograph-measurement errors, (4) tracking errors, and (5) unrepresentative rawinsonde observations.

The principal sources of cloud-velocity deviation from observed winds are ranked in order of their significance to identify the critical areas needing improvement. It appears that cloud-height uncertainty is the most significant cause of deviations, particularly about upper cloud heights. Work aimed at reducing this uncertainty is just beginning.

To point out the unique problems involved, we discuss the technique of selecting and classifying cloud targets. The procedure is a subjective skill dependent upon the analyst's meteorological judgment.

Despite the problems—many as yet unsolved—the single earth-synchronous satellite, with its immense areal coverage and high frequency of coverage, provides an important new source of data from remote regions.

1. INTRODUCTION

Pictures received from geostationary satellites have provided meteorologists with a new type of upper air data. Each of the present geostationary satellites is designated an Advanced Technology Satellite (ATS). ATS 1 is located over the Equator at 150°W, while ATS 3 has been positioned at several different longitudes from 45°W to 85°W. Several pictures are taken during the lifetimes of trackable cloud patches, hence cloud motions can be measured. Certain clouds are advected by the ambient winds; consequently measurements of such motions (cloud velocities) provide estimates of the winds. Wind estimates made in this manner have the advantage of wide coverage. The accuracy and representativeness of these wind estimates are uncertain, however, because we derive the cloud velocities by exploiting characteristics of cloud organization only recently discovered and, as yet, only partly understood.

Section 2 describes the data used for this study and the procedure for assessing accuracy of our wind estimates. Section 3 presents an assessment of error of wind estimates based on measurement of cloud velocities. Accuracy is enhanced by a skillful selection of cloud targets, the subject of section 4. Section 5 identifies the various sources of deviation of estimated cloud velocities from observations. Section 6 summarizes our results.

2. PROCEDURES AND DATA

PROCEDURE FOR DERIVING CLOUD VELOCITIES

In principle, the satellite camera is stationary relative to the earth so that fixed earth features are photographed in the same position on all pictures—only clouds change location on the image. Time-lapse movies are produced to animate cloud motion; the motion, in turn, is measured on a projected display. The steps are:

1. Preparing a movie sequence by photographing, with a movie camera, the individual images that were taken from the satellite at intervals up to 30 min.[1]
2. Projecting the movie sequence repeatedly onto a worksheet by means of an endless loop.[1]
3. Selecting clouds as targets and marking their initial and final positions on the worksheet, classifying cloud type.
4. Measuring, scaling, and recording the cloud velocity vectors.

PROCEDURE FOR ESTIMATING ACCURACY

To measure the accuracy of wind estimates, we must compare them with observed winds at the level of the cloud target. But cloud height is difficult to derive; soundings of temperature and humidity do not provide adequate information, and below −40°C humidity is not reported. Consequently, it was necessary to devise some other means of specifying cloud height; one that does not rely on radiosonde data.

Heights of target clouds were estimated from nearby wind soundings. It was assumed that the minimum vectorial difference between cloud velocity and balloon velocity occurred at the cloud level. This level of minimum velocity difference was designated as the "level of best fit" (LBF). To find LBF, we plotted each cloud velocity on the hodograph of a nearby upper air observation as shown in figure 1. The interpolated level (within the

[1] Two similar closed-circuit television systems have been developed to replace the movie camera and projector. The equipment designed and built at Stanford Research Institute (SRI) is described by Serebreny et al. (1970*b*). The Electronic Animation System developed at the National Environmental Satellite Service (NESS) has not been reported in the literature. Basic procedures for selecting and tracking clouds are unchanged, however, and some of the measurements included in our statistics were obtained by SRI on their equipment.

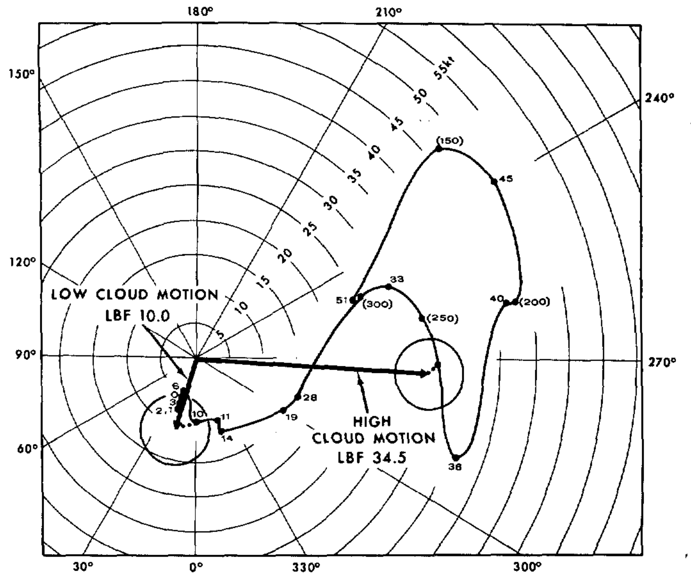

FIGURE 1.—Typical hodograph illustrating the method of deriving level of best fit (LBF) of target clouds from the observed winds. Heights are given in thousands of feet and, in parentheses, in constant-pressure levels. Cloud velocities are represented by vector arrows with 5-kt error circles centered on their endpoints.

troposphere) at which the hodograph vector was nearest the endpoint of the cloud velocity vector was taken to be the LBF. Five-kt circles are centered on each cloud velocity vector in figure 1 to illustrate the effect of a 5-kt wind error on the LBF. Depending upon the direction of error, the lower level LBF in this instance could be anywhere in the layer from the surface to 10,500 ft, while the upper level LBF could be anywhere in the layer from 34,000 to 35,000 ft. Such height ranges may be greater or less than this example, depending upon the structure of wind in the vertical. Where the vertical wind shear is small, a 5-kt circle will encompass a very deep layer and in such cases improbable LBF's can be derived. The wide range of LBF's is, in part, due to that wind-error effect.

The LBF probably often yields a good estimate of the actual cloud height, but more important for our purposes, the distribution of the heights indicates the range of heights of the selected targets. Such distributions are a measure of the extent to which the analyst has properly classified the cloud type. Hence, hodographs are a useful tool for this investigation. Unfortunately, they cannot be applied by the operational ATS analyst.

In an operational situation, the ATS analyst does not have hodographs and cannot determine the LBF. Therefore, the cloud velocities must be used for map analysis at some level that is representative of the cloud type classification, rather than at the individual LBF. The distribution of LBF's indicates which levels are most representative. Accuracy of cloud velocities as wind estimates, evaluated at two such representative levels for low and high clouds, is presented in section 3.

TABLE 1.—*Location, date, and number of ATS wind estimates*

Location	Date	Number of cloud velocities	
		Low-level clouds	High-level clouds
Pacific Ocean	April and August 1967	47	19
Pacific and Atlantic Oceans (derived by SRI)	April, August, and November 1967	64	--
United States	April 1968	--	117
Gulf of Mexico and Carribean	June 1968	39	72
Pacific Ocean (GARP* data)	November 1969	462	356
	Total	612	564

*Global Atmospheric Research Program

DATA USED

The data sample used in this investigation consists of measurements of approximately 600 low-cloud motions and about 560 high-cloud velocities. In some cases, more than one cloud velocity was compared to a single rawinsonde observation. The maximum distance between target clouds and their associated upper air stations was 150 n.mi.

The time between upper air sounding and the ATS picture sequence ranged up to 6 hr in the Atlantic and United States and up to 4 hr in the Pacific. ATS 3 picture sequences usually are centered near 1800 GMT, at which time few soundings are made. In those cases, the bracketing 1200 and 0000 GMT soundings were used to interpolate an 1800 GMT sounding. ATS 1 sequences frequently end near 2300 GMT, so the nearest 0000 GMT sounding was usually less than 3 hr from time of the cloud velocities. Table 1 shows dates and general areas over which cloud velocities were derived for this study.

3. ACCURACY OF CLOUD VELOCITIES AS WIND ESTIMATES

Statistics presented in this section measure two aspects of accuracy. First, we assess the degree of success achieved in judging cloud genera by examining the dispersion of LBF's. Second, we summarize deviations of cloud velocities from nearby rawinsonde observations at two levels which are shown to be most representative: one summary for low clouds, a second for high clouds. Such deviations measure accuracy of the cloud velocities as wind estimates for two specific analysis levels.

These results represent the state of the art during the past few years. The quality of this sample is not uniform because the analysts' skills varied. The critical importance of skill will become clear in the next section.

DISTRIBUTION OF LEVELS OF BEST FIT

The heights of the LBF's for low- and high-cloud targets were tabulated at 2,000-ft class intervals. Frequencies of occurrence appear in figures 2 and 3. For low clouds (fig. 2)

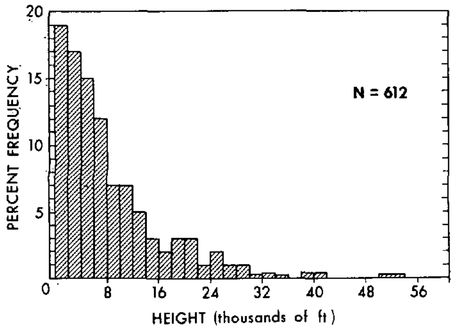

FIGURE 2.—Frequency, in percent of total low-cloud sample, versus height of LBF. Heights are shown in 2,000-ft class intervals.

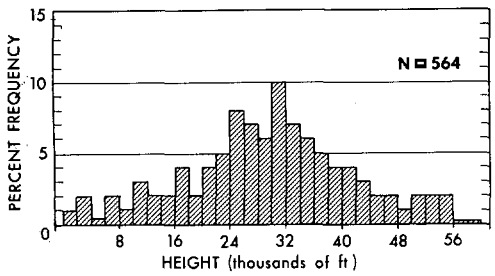

FIGURE 3.—Same as Figure 2 but for the high-cloud sample.

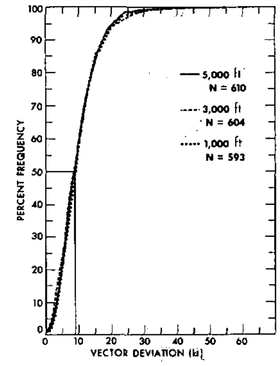

FIGURE 4.—Magnitude of vectorial deviations of low-level cloud velocities from observed winds at 1,000, 3,000, and 5,000 ft versus cumulative frequencies.

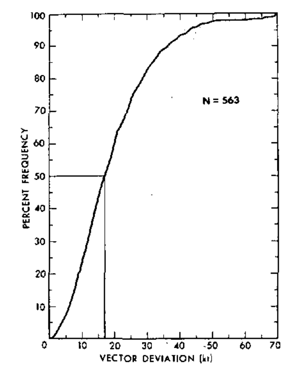

FIGURE 5.—Magnitude of vectorial deviations of high-level cloud velocities from observed winds at 30,000 ft versus cumulative frequency.

the mode falls in the lowest class interval. Taken at face value, this suggests that wind estimates from low clouds are representative of the layer from surface to 2,000 ft. However, this modal level is not necessarily the elevation where the deviations are minimized. Figure 4, discussed later, shows that there is little to choose between various low levels. For this sample it appears that the "deviation-minimizing" level is 3,000 ft, but a different sample could well favor another level.

Figure 3 illustrates the height distribution of the upper cloud LBF's. The principal mode and the median LBF are quite near 30,000 ft. However, a significant fraction of high-cloud targets lies below 20,000 ft, suggesting that, despite the analysts' efforts to track only cirrus, many middle-cloud targets were selected.

Two conclusions are suggested by these figures: (1) under operational conditions when no cloud height data are available, the low-cloud motions are best applied to 3,000-ft to 5,000-ft analyses and the upper cloud motions are best applied to the 30,000-ft analysis; (2) it is clear that the height uncertainty is greatest for high-level clouds.

VECTORIAL DEVIATIONS AT 3,000 AND 30,000 FT

From the viewpoint of the user, the accuracy of wind estimates is measured by the deviations of cloud velocities from those of actual winds at the level to which the estimate has been assigned—namely, the 3,000- and 30,000-ft levels. From the user's viewpoint, therefore, wind estimates might be in error even if the *cloud velocity* were precise. For that reason we tabulated, for each cloud motion vector, the magnitude of vector deviation and the magnitude of directional deviation from the observed wind at those two "representative" levels.

Cumulative frequencies of deviation of low- and high-cloud motions from observed winds are shown in figures 4 and 5. Curves of deviation at 1,000 and at 5,000 ft are also shown on figure 4 to illustrate two points. First, with a sample that consists of a wide variety of low clouds, the cloud velocities correspond reasonably well to the flow at various low levels. Second, comparison of these curves shows that the deviation-minimizing level is not necessarily the modal level of the LBF's; it tends toward the mean LBF.

Figure 4 shows that half of the targets judged to be low clouds deviated from the observed 3,000-ft wind by no more than 9 kt, while figure 5 shows that half of the targets judged to be cirrus deviated no more than 17 kt from the 30,000-ft winds. This larger deviation of upper level cloud velocities is partly the consequence of the greater dispersion in elevation of upper level targets that was shown in figure 3.

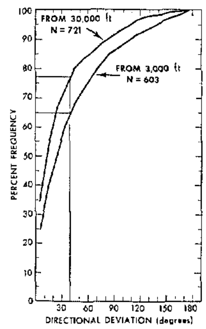

FIGURE 6.—Magnitude of directional deviations of low-level cloud velocities from 3,000-ft observed wind and corresponding deviation of high-level cloud velocities from 30,000-ft observed wind, versus cumulative frequencies.

DIRECTIONAL DEVIATIONS

Despite the size of the vectorial deviations, the directional patterns correspond reasonably well to those of the real flow patterns at the two representative levels. Hence, streamline analyses of cloud directions delineate cyclones and anticyclones, troughs and ridges, and sometimes more subtle flow configurations. This characteristic is illustrated by the cumulative frequencies of directional deviations given in figure 6. More than 75 percent of the high-level cloud directions were within $\pm 40°$ of the 30,000-ft wind direction, while 65 percent of the low-level directions were within $\pm 40°$ of the 3,000-ft wind direction.

4. SELECTING AND CLASSIFYING TARGET CLOUDS

The intent of this section is not to present a complete guide for the ATS analyst, but to stress the type of clues that must be employed to surmount some of the problems inherent in these data. The selection procedure is subjective, depending upon the meteorological knowledge of the analyst in a manner that is shown by the following outline. The goals of the selection procedure are to classify cloud genus and to discriminate between "passive tracers" and those cloud targets that are unusable because they are displaced by nonadvective mechanisms. Some targets can be seen to move in directions totally inconsistent with the wind at any level; therefore, tracking every visible target would degrade the quality of wind estimates. As a consequence of this selection process, only a fraction of all visible clouds are tracked.

Motion, displayed by means of animation, provides a powerful aid to meteorological interpretation. Animation enables one to examine pattern behavior—a significant advantage over instantaneous views. Not only are brightness, texture, and pattern of clouds disclosed, but so are time changes and relative motions of cloud layers. Such pattern behavior enables one to deduce a great deal more about the vertical structure of the flow pattern, hence about the synoptic regime, than is possible with "snapshot" pictures.

CLASSIFICATION OF CLOUD TARGETS

Typically, the analyst decides on cloud type by first determining the synoptic situation. Cloud genus is then deduced by judging how the cloud behavior fits the appropriate synoptic model. Where it is not possible to reconcile a target's behavior with the synoptic situation, it is prudent to omit that target.

The known relationships between satellite pictures and synoptic situation provide the starting point. Motion of clouds aids the analyst in applying the following guidelines:

1. Locate cyclones, fronts, jet streams, squall lines, and intertropical convergence zones by looking respectively for such indicators as spirals, large bands, abrupt cloud edges, and lines or zones of bright cloudiness.
2. Determine whether jet stream indicators are consistent with the position of cyclones and fronts.
3. Identify cold air masses by looking for bright globular cloud masses behind cold fronts near cyclonic centers.
4. Determine stages of cyclone development by the character of spirals or waves.
5. Determine interaction between air masses and underlying surfaces by looking, for example, for cloud types typical of cold advection over warmer water or warm advection over colder water.

Once the synoptic situation is determined, observations of cloud characteristics and cloud motion aid the analyst in segregating cloud layers and in specifying cloud types. The following guidelines should be considered when determining cloud level and cloud type:

1. Clouds at different levels can be distinguished by their contrasting speed and direction.
2. Cloud patches moving in contrasting directions in the same area frequently suggest, by considering climatology, which layer is low cloud and which layer is high cloud. For example, tropical easterlies are easily separated from upper level westerlies.
3. Cumulonimbi in a field of cumuli produce cirrus that usually move differently than the low-level clouds.
4. Cirriform clouds usually move faster than low-level clouds, particularly at midlatitudes.
5. High clouds in well-developed tropical cyclones move slowly and both cyclonically and anticyclonically, whereas low and middle clouds move rapidly in a cyclonic direction.
6. Bright clouds with sharp edges usually are cumuliform and are easily tracked.
7. Bright globular masses behind cold fronts and near cyclonic centers are cumuliform—usually with some vertical development.
8. Large globular masses in the southeastern sector of anticyclones are cumuliform—usually with little vertical development because they are restricted by inversions.
9. Clouds influenced by coast lines and by ocean temperatures are low-level clouds.
10. Thin clouds with diffuse edges tend to be cirriform and are less easily tracked than cumuliform and middle clouds.
11. Clouds associated with jet streams are often cirriform. Beware of the large masses of bright multilayered cloud associated with jet streams, for the bright middle clouds will often obscure the thin gray cirrus of jet stream level.
12. Large uniform cloud masses with few distinguishable elements tend to be middle clouds that are difficult to track.

SELECTION OF PASSIVE TRACERS

Selection of passive tracers is made concurrently with the classification of clouds. Some guidelines are:

1. Follow the same point on cloud clusters and patches rather than lines, bands, or areas of equal brightness.
2. Use only those clouds moving at speeds and in a manner that is consistent with the synoptic situation. Beware of motions which appear to move through a pattern of cloud, alternately suppressing

TABLE 2.—*ATS Cloud velocity deviations from rawinsonde observations; magnitude of vector deviations for various cumulative percentages of sample is shown. N is the total number of measurements.*

Cumulative percent of sample	Low-cloud velocities (N=612)			High-cloud velocities (N=564)		
	Total at 3,000 ft	Deviation at LBF	Part due to height uncertainty	Total at 30,000 ft	Deviation at LBF	Part due to height uncertainty
	(kt)	(kt)	(kt)	(kt)	(kt)	(kt)
50	9	3	6	17	5	12
75	13	6	7	25	10	15
85	16	8	8	31	13	18
90	18	9	9	36	15	21

and enhancing brightness. This type of motion often conflicts with motion of the individual cloud elements in the same layer and is probably due to gravity waves. Upward motion in crests of such waves enhances cloudiness, and downward motion in troughs suppresses cloudiness. These motions are frequently seen in inversion-dominated low clouds and at various upper levels near cold fronts. As expected from theory, the orientation of waves and their direction of motion bear no fixed relation to the ambient wind.

3. Use clouds which show the least change during the time-lapse sequence.

4. Take care in tracking clouds that appear to penetrate vertical shear layers. In these cases, try to track the upshear edge rather than the center of mass. For example, in areas of active convection the cloud area grows rapidly because of anvil growth. The origin of the anvil (the brightest area at rear of the growth area) moves with the middle- and low-level wind. The leading edge of the anvil, while advancing with the high-level wind, may be moving more slowly than the wind because of evaporation. Thus the *leading edge* of growing cirrus plumes should be avoided.

DISCUSSION OF SELECTION TECHNIQUES

The present shortcomings of our selection procedure account for a significant part of the deviations in table 2. The range of LBF's shown in figure 3, for example, would have been reduced appreciably had the analyst succeeded in selecting cirrus targets exclusively. The errors shown in table 2, due to height uncertainty, would have been reduced.[2]

Misclassification of cirrus can be minimized by close attention to texture and brightness revealed on high-quality pictures and by a cautious choice of targets. A good practice is to discard a target if its classification is doubtful. But these improvements alone cannot eliminate error due to height uncertainty. Cirrus occurs over a wide range of altitudes; consequently, vectors derived from cirrus motions cannot correspond to any one representative level. Use of a single level will produce significant error in regions where vertical shear is large.

Can cirrus altitudes be subclassified? We feel they might be and are just beginning to examine the possibility. Cirrus which flanks a jet stream is recognizable on satellite pictures. Cirrus related to a polar jet probably forms at an altitude different from cirrus associated with a subtropical jet. High clouds behind a trough may be at different heights than cirrus ahead of the trough. Cirrus being carried away from tropical disturbances may lie at yet a different elevation. If these considerations enable one to assign wind estimates to representative levels other than 30,000 ft, the "height uncertainty" error will be reduced.

[2] In a study sponsored by NESS, Serebreny et al. (1970*a*) found that deviations of high-level cloud velocities from the 30,000-ft wind were reduced from 20 to 17 kt by eliminating those targets whose LBF fell below 20,000 ft (eliminating, thereby, the lower clouds that had been mistaken for cirrus).

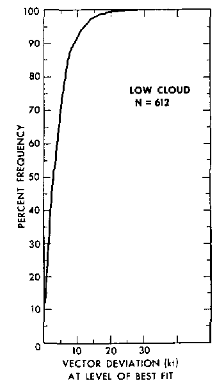

FIGURE 7.—Magnitude of vectorial deviations of low-level cloud velocities from observed winds at their individual LBF's, versus cumulative frequencies.

Wind estimates at low levels also can be improved by this approach. An example of very small error due to height uncertainty can be seen in a case study by Fujita (1969). He derived many cloud velocities in tropical areas where climatology insured that most targets were suppressed low-level stratocumuli.

5. SOURCES OF ERROR

Five significant sources contribute to the error of wind estimates at 3,000 and 30,000 ft. These are:

1. Uncertainty of target cloud height,
2. Nonadvective cloud motion,
3. Errors of measurement,
4. Errors in tracking cloud targets, and
5. Errors due to nonrepresentative rawinsonde observations. (While this does not affect the accuracy of our wind estimates, it does contribute to the deviations.)

Although data available at this time are inadequate to measure the individual contribution of each source of error, we believe that these are the principal sources, listed in approximate order of decreasing importance.

UNCERTAINTY OF TARGET CLOUD HEIGHT

Cloud targets are tracked at a variety of elevations, but for reasons already discussed, we assign the wind estimates to specific representative levels. Deriving cloud velocities at various elevations and assigning them to specific levels for analysis is an error source, from the user's viewpoint, which we call uncertainty of cloud height. To the extent that our LBF's represent actual cloud heights, we can deduce the influence of cloud height uncertainty. We shall see that this factor accounts for over half of the error at 3,000 and 30,000 ft—a result found by comparing the deviations summarized in figures 4 and 5 with deviations at the LBF.

Figure 7 presents cumulative frequencies of magnitude of vectorial deviations between low-level cloud velocities and observed winds *at their individual LBF's*, while figure 8 shows a similar curve for high-level cloud velocities. About 70 percent of the low-level vectors deviated from observed winds (at LBF) by 5 kt or less. Slightly more than

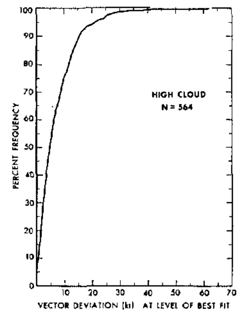

FIGURE 8.—Same as figure 7 but for the high-level cloud sample.

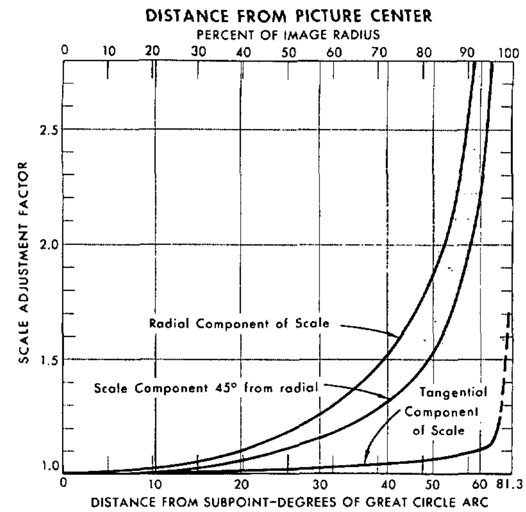

FIGURE 9.—Scale adjustment factors for radial vectors, for tangent-vectors and for vectors 45° from radials, as a function of distance from picture center. This factor is the ratio of image scale at the picture center to the image scale at various distances from the center.

50 percent of the high-level vectors deviated from the observed wind 5 kt or less at their LBF's These deviations stem from the combined influence of all error sources with the exception of cloud height uncertainty.

Figures 4 and 5, on the other hand, summarize the influence of all error sources, including cloud height uncertainty. Hence, the differences between figures 4 and 7 and between 5 and 8 reveal the contribution of height uncertainty to the total deviation; several such differences are tabulated in table 2. For half of the cloud velocities at low levels, the deviations at LBF did not exceed 3 kt, while half of the deviations at 3,000 ft did not exceed 9 kt. Therefore, an error up to, but not exceeding, 6 kt can be attributed to the cloud height uncertainty.

The last column for each cloud type in table 2 shows that the largest part of wind-estimate errors at the two representative levels is due to cloud height uncertainty. In all portions of the sample, the error due to height uncertaintly is greater by a factor of two for the 30,000-ft wind estimate than for the 3,000-ft estimate. This is not surprising, in view of the great range of high-cloud heights.

NONADVECTIVE CLOUD MOTION

We have no way of measuring the influence of nonadvective motions. The deviations illustrated in figures 7 and 8 suggest that the analysts selected a few improper targets and tracked nonadvective cloud motions. We have found that with increased experience ATS analysts become more selective. This suggests that they detect and reject a greater proportion of nonadvected features. It is not surprising that our sample, in part derived by inexperienced analysts, includes some improper targets.

ERRORS OF MEASUREMENT

Misregistration: The largest measurement errors are the result of imprecise registration of the first and last pictures of the sequence. Apparent motion of fixed points on the earth's surface are thereby added to the real motion of cloud targets. Picture-to-picture registration can be achieved by matching earth features, but precision is limited by resolution of the system. Even when landmarks are matched to that precision, distortion that varies from picture to picture puts portions of the image out of register.

On the basis of analyzing hundreds of ATS pictures, Fujita (1970*a*) estimated that good-quality ATS3 pictures can be registered within 10 km at the subpoint. The error becomes larger elsewhere on the image because the scale varies across the image disk. If, for example, 1 mm on the image corresponds to 10 km at the subpoint, 1 mm near the horizon might correspond to 20 km or more, depending on scale variability.

Variability of scale: Image scale is a function both of distance from the satellite subpoint (center of the image disk) and the orientation of the vector being measured. Scale varies inversely with distance from the subpoint and directly with the angle between the vector and the image radial. Line segments parallel to the radials are foreshortened because the earth's curvature presents those segments to the camera partly end-on. The same segment lying perpendicular to the radial will not be foreshortened. The only scale variation of tangential segments is caused by increase of slant range to the satellite resulting from increased subpoint distance.

Figure 9 shows the factors required to adjust radial and tangential components. The ordinate is labeled in terms of the factor necessary to adjust the image scale in areas distant from the subpoint to the image scale at the subpoint. The curve for the radial component shows the large-scale change that is the combined effect of foreshortening and increased distance from the subpoint, while the curve for the tangential component corresponds to the change due to increasing slant range only.[3]

The effect of scale variability on misregistration error cannot be assessed, because the direction of misregistration is unknown. We can state only the upper and lower limits after we have estimated the magnitude of misregistration at the subpoint. A given misregistration will

[3] These nonlinear scale changes are, of course, taken into account when cloud displacements measured on the image are translated into distances over the earth's surface. Each cloud motion in the image plane is resolved into its radial and tangential components and the appropriate scale factors are applied.

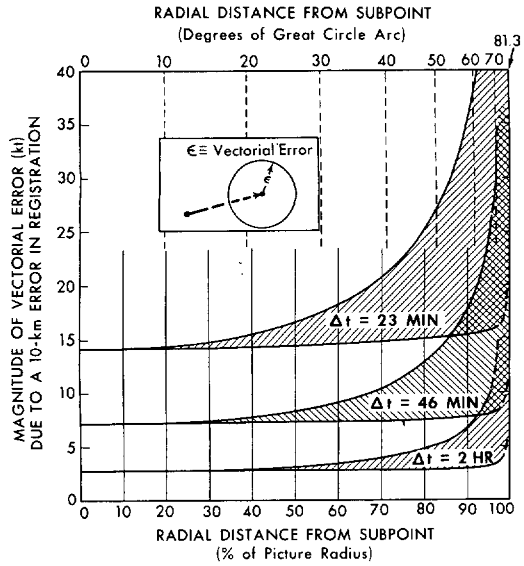

FIGURE 10.—Magnitude of the vectorial error of cloud motions resulting from a 10-km error of registration at the subpoint, as a function of distance from picture center. Each shaded area represents errors corresponding to different time periods of the animated sequence. The range of errors (hatched areas) for each time interval corresponds to the range of scale factors (fig. 9) determined by the orientation of the error vector.

produce larger errors in that part of the field of view where it has caused a radial displacement than where it has caused a tangential displacement.

If, for instance, misregistration caused the subpoints of the first and last pictures to be displaced east-west by 10 km, then at 50 degrees of latitude north and south of the subpoint the error would be only 10.5 km, while at the same distance east or west of the subpoint, the error would amount to 16.7 km. Fortunately, the influence of misregistration is minimized by proper selection of the time interval for animation.

Effect of time interval: In addition to scale and misregistration considerations, measurement accuracy of velocities depends on yet another factor, the total displacement distance of the target cloud. Where the displacement is large compared to the misregistration error, neither speed nor direction will be much affected; but where the cloud displacement is less than the misregistration error, the computed velocity might have speed errors exceeding 100 percent or direction errors of 180 degrees. It is clear that reliable computation of velocity by our procedures can be accomplished only where the target displacements are relatively large, that is, where the time interval of the sequence is long enough to permit clouds to move a few tens of kilometers.[4]

The time interval ultimately is limited by cloud lifetimes; nonetheless, it is possible to use 2- to 3-hr sequences. Fujita (1970*b*) examined various types of cloud targets and demonstrated that a significant number of targets existed for this length of time. Nearly all of our sample was derived from sequences upward of 2 hr. The advantage of using long sequences is illustrated in figure 10.

Based on the assumption of a 10-km misregistration at the subpoint, the diagram illustrates the magnitude of vectorial error of cloud velocity that would result from three different time periods. The upper limit of each curved area corresponds to the error produced if the misregistration is radially oriented while the lower limit corresponds to the error vector that is tangentially oriented. It is clear that the influence of a 10-km registration error at the subpoint is tolerable if the animation period is 2 hr or longer.

Effect of orbital inclination: Two images can be registered over their entire field of view only if the camera is fixed relative to the earth. Any inclination of the orbital plane produces a north-south motion of the satellite and precludes whole-image registration. Cloud velocities can be derived, nonetheless, by measuring their apparent motion and subtracting the apparent motion of fixed points on the earth. Because the number and distribution of visible landmarks is inadequate to permit direct measurement of apparent earth motions, these motions must be computed from the geometry of the problem. This requires a very accurate specification of the position and orientation of the spin-axis of the spacecraft.

Accuracy suffered in many of our cloud velocity determinations because the orbital plane of ATS 1 was inclined. Corrections were applied, but inadequate information concerning the satellite parameters and other pertinent geometrical data at the time the velocities were derived made the corrections themselves somewhat imperfect. Consequently, the misregistration in about half our sample was somewhat greater than 10 km, possibly averaging 15 to 20 km.

Errors in tracking: Measurement errors affect both high- and low-level cloud vectors to the same degree. Tracking errors, however, appear to affect the two levels to different degrees. "Tracking error" refers to failure to track the same cloud feature throughout the sequence.

Cumulus clusters frequently appear as bright spots. Cirrus targets, on the other hand, are likely to be filmy and poorly defined, suggesting that the tracking error will be greater for the upper level. Columns 3 and 6 of table 2 show deviations of high-level cloud velocities at their individual LBF's to be nearly double those at low levels for all portions of the sample. This tends to confirm our impression that high clouds are more difficult to track than low-level clouds.

Discrepancies due to nonrepresentative rawinsondes: Some of the deviations between our wind estimates and rawinsondes are due to errors in the sounding data. Klein (1968) showed that the root-mean-square errors of rawinsonde measurements vary from 5 to 17 kt, depending on wind speeds. The average speeds encountered in this study suggested that the appropriate rawinsonde error is at the lower end of that range.

[4] This relation of displacement to error is critical for all techniques that measure cloud displacement. For example, computer procedures have been developed (Leese et al. 1971) that match cloud patterns to detect displacement of cloud fields, from picture pairs half to three-quarters of an hour apart. Since many cloud displacements during this interval will be no greater than 5 to 10 n.mi., clouds must be mapped (earth-located) with an error substantially less than 2 n.mi., for reliable velocities—a figure comparable to the resolution limitation of the present ATS pictures.

Further discrepancies are caused by wind changes between the time of upper air sounding and the time of ATS picture sequence, and change of the flow between the balloon location (downwind from islands) and the cloud target location (sometimes upwind from the islands).

We cannot measure the contribution to wind estimate discrepancies of nonrepresentative rawinsondes, but certainly some discrepancies were so produced. Therefore, the "errors" presented here somewhat overestimate the true deviation of our estimates from actual winds at 3,000 and 30,000 ft.

6. SUMMARY

Generally, two levels of cloud motion are easily seen—one at cumulus levels and one at cirrus levels. To compare cloud velocities with balloon velocities, we had to devise a means of specifying cloud heights. This specification was made by assuming that the minimum vectorial deviation between cloud motion and balloon motion occurred at the cloud level—a level designated as the "level of best fit" (LBF).

The distributions of heights of LBF for low clouds and for high clouds indicated that low-cloud velocities corresponded most closely to winds at 3,000 ft and that high-cloud velocities corresponded most closely to winds at 30,000 ft. Until better height information is available, cloud velocities of this type should be regarded as wind estimates at those two levels for map-analysis purposes.

A measure of errors introduced by using cloud velocities for map analysis has been obtained by summarizing the deviations of cloud vectors from observed winds at nearby rawinsonde stations, at their representative levels. Table 2 lists such deviations for various parts of the sample and shows that upper level estimates have double the deviation of those at low levels.

Despite the vectorial deviations listed in table 2, the directional deviations are modest. Hence, streamline analyses made from cloud velocities provide realistic flow patterns at the two representative levels. This characteristic, together with the prodigious areal coverage provided by a single geostationary satellite, shows the importance of this new source of data.

The selection technique is a subjective procedure that depends on a correct deduction of the synoptic situation. Experience has shown that meteorological judgment enables one to select "passive tracers" and classify their cloud types. Animated picture sequences are of great help in meteorological interpretation, in distinguishing between different layers of clouds, and in identifying nonadvective motion.

An examination of error sources revealed that, apart from nonadvective cloud motions, measurement errors arise chiefly from misregistration of pictures and image distortions which are different from picture to picture. Inclination of the orbital plane also creates registration problems because the entire field of view cannot be registered when the satellite moves relative to the earth. The corrections that must be applied depend upon very precise knowledge of the satellite position and orientation. Lack of such data has degraded accuracy of the sample used here.

Accuracy of computed velocity also depends on the total length of the cloud trajectory, because misregistration error has little effect if it is small relative to target displacement. The influence of misregistration can therefore be minimized by using sequences long enough to produce large cloud displacements. With the registration accuracy that is achieved with good-quality pictures, a sequence 2 hr or longer will reduce this type of error to 2–5 kt.

Nonrepresentative rawinsondes have undoubtedly contributed to the discrepancies between wind estimates and observed winds. For that reason, our various statistics somewhat overestimate the actual error of our estimates.

In conclusion, the accuracies reported here represent the state of the art as it existed during the past few years. The greatest source of discrepancy between cloud velocities and rawinsondes at the two representative levels is the uncertainty in estimating the height of high-level clouds. It follows that the greatest opportunity for improvement is in refining the estimate of high-cloud heights. Work along this line has already commenced. Moreover, infrared images will be obtained by the next generation of geosynchronous satellites. Derived cloud-top temperatures will aid in estimating their elevation.

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